# Advanced Energy Materials

## Energy Harvesting Technologies for Tire Pressure Monitoring Systems

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# Energy Harvesting Technologies for Tire Pressure Monitoring Systems

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## Abstract

Tire Pressure Monitoring Systems (TPMS) are becoming increasingly important to ensure safe and efficient use of tires in the automotive sector. A typical TPMS system consists of a battery powered wireless sensor, as part of the tire, and a remote receiver to collect sensor data, such as pressure and temperature. In order to provide a maintenance-free and battery-less sensor solution there is growing interest in using energy harvesting technologies to provide power for TPMS. This paper summarizes the current literature and discusses the use of piezoelectric, electromagnetic, electret and triboelectric materials in a variety of harvesting systems.

## Keywords

Energy harvesting, tire pressure monitoring systems, self-powered sensors, battery-less sensors, automotive devices.

## 1. Introduction

The quest to exploit renewable energy sources has recently prompted significant research in the field of energy harvesting, wherein clean useful energy is extracted by a variety of novel methods from existing ambient sources that would otherwise be wasted. As interest in energy harvesting continues to grow, a wide range of applications begin to emerge. One promising approach for harvesting is to provide sustainable power for wireless sensors, thereby reducing their reliance on batteries which can be toxic to the environment, have a limited lifespan and require periodic replacement. The integration of energy harvesting technologies not only secures autonomous operation of these systems, but also alleviates maintenance costs, especially for sensors operating in harsh environments or those placed in inaccessible locations. Recent technological advances in wireless electronics that has resulted in smaller, more efficient and less power-demanding devices have also spurred interest in energy harvesting technologies to replace batteries.

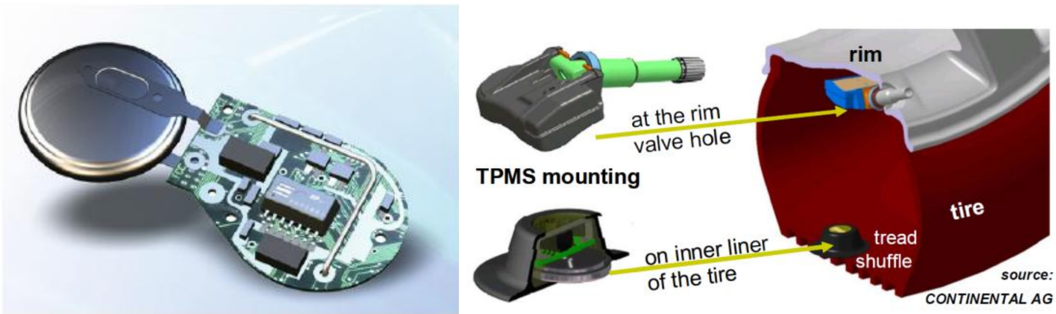
One of the promising application domains in the automotive industry is harvesting energy for tire pressure monitoring systems (TPMS). An early investigation of energy harvesting technologies for TPMS was presented by Roundy [1] and Kubba *et al.* [2] recently provided an excellent and detailed overview of TPMS systems. TPMS are becoming increasingly mandatory in the automotive market as more stringent environmental regulatory frameworks [3] are being established to lower fuel consumption and $CO_2$ emissions. Maintaining a correct tire pressure also contributes significantly to passenger safety as it directly affects the vehicle's handling and control. Underinflated tires can cause high heat generation, which leads to rapid tire wear, tread separation, blow-out and loss of vehicle control. Vehicles with underinflated tires also suffer from reduced lateral stability and require longer stopping distances, especially on wet roads. Overinflated tires, on the other hand, suffer from poor grip and reduce the vehicle's stability. Tire failure at high speed is a particular concern since it increases the potential for vehicle roll-over.

To alleviate these problems, TPMS are being designed to continuously monitor the air pressure inside automotive tires. The purpose of TPMS is to provide a warning signal if the air pressure inside the tire falls outside maximum/minimum safe limits. Conventional TPMS consist of tire pressure modules that are either installed onto the wheel rim, inside the tire cavity, or are attached to the inner lining of the tire. The pressure sensors continuously measure the air pressure, as well as other physical quantities such as temperature and acceleration, and transmit the readings to an onboard receiver/display by radio frequency transmission.

The *direct* and *indirect* methods are used to monitor tire pressure. The indirect system relies on the fact that an underinflated tire, with a smaller diameter, will rotate faster than a correctly inflated tire. For these systems, each wheel contains a rotational speed sensor and the speed of each wheel is compared to the average speed of all the wheels to determine if one is rotating significantly faster than the others. Indirect methods also include those measuring the distance of the wheel centers to the ground and identifying an underinflated tire as one with its wheel center closer to the ground. The direct system has sensors within each tire to measure the pressure directly and this data is relayed to the driver in real-time. Although the systems vary in transmitting options, most direct systems use radio frequency (RF) signals to send data to an electronic control unit.

Currently, the electrical power for TPMS is provided almost exclusively by batteries, which have a limited lifespan and require periodic replacement. The typical architecture of a TMPS consists of a micro-machined pressure sensor, a micro controller for processing, an RF transmitter to transmit the data to a central receiving unit and a battery as a power source. Automobile manufacturers require a battery life of at least 5 years, and a battery capacity of 220-600 mAh for TPMS [4] [5].

Figure 1a shows the main components of a direct TMPS module [5], which reveals that the battery takes up a significant volume of the TPMS module. The TPMS is often mounted either at the wheel rim or in the inner liner of a tire, as indicated in Figure 1b, and we will see later that energy harvesters have been considered in both locations. Competing technologies based on energy harvesting technologies should therefore target reducing the battery size, weight, environmental impact, maintenance and cost.




(a) (b)

**Figure 1. (a) Components of a battery-powered TPMS module [5] (with kind permission from Springer Science and Business Media), the battery is a button cell for scale. (b) TPMS mounting at the wheel rim or in the inner liner of a tire [6].**

When developing an energy harvesting platform for TPMS, the power requirement of a typical TPMS sensor is a key issue in the design of a system that matches the traditional battery power. Recent studies show that power levels in the order of 4 mW can be harvested from a rotating wheel [7], which is commensurate with the power requirement of a TPMS. Figure 2 shows the power requirements for a range of transmission rates, as presented by Kubba et al. [8]. Approximately 450 μW is required when the transmission rate is once per second, which serves as a good estimate of the required power output of an energy harvester. In addition to data transmission, Löhndorf [9] highlighted that other contributors to power consumption include power-down current, pressure measurement and motion detection. The components of a TPMS should also be small to avoid detrimental tire balance forces and this imposes design constraints on the size of the TPMS components and energy harvester.

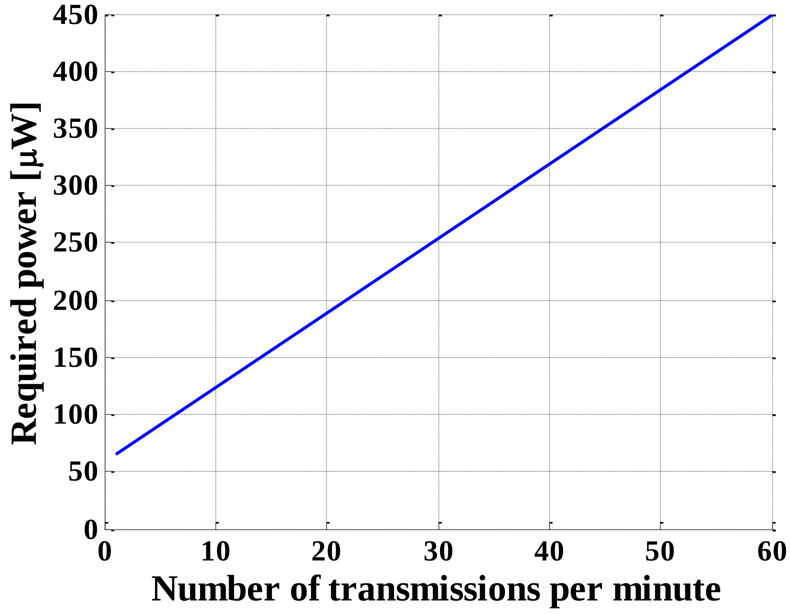



Figure 2. Required power versus transmission rate (adapted from [8]).

## 2 Energy harvesting for TPMS

In automotive applications, some of the appealing sources of energy to be extracted include heat, light and mechanical motion. An overview of the most prominent energy harvesting technologies and devices in the automotive environment has been presented in [10]. Emphasis in this review article, however, is placed on reviewing the materials and systems used for extracting energy for TPMS where the primary energy source is derived from the rotational motion of the wheel. Spinning tires are attractive for energy harvesting since the source of power is located where the power is needed, hence there is no need to transmit power over long and logistically infeasible paths using hard wires. This review examines research on harvesting the rich source of kinetic energy from rolling tires and its potential to provide sufficient power for TPMS without detrimentally affecting its functionality. The review will present the current state-of-the-art, and to present future prospects and challenges in the field of energy harvesting from TPMS.

## 2.1 Classification of energy harvesting technologies for TPMS

The mechanical energy associated with a rolling wheel is the most popular form of energy harvesting for TPMS, compared to heat and light. In each case, energy harvesters are designed and mounted so as to extract energy most efficiently. At the present time, the competing energy transduction mechanisms employed for TPMS are piezoelectric, electromagnetic, electrostatic, magnetostrictive, triboelectric and electroactive polymers. These materials and approaches will be briefly introduced before discussing how they are employed to generate power. Specific examples are described in detail later in the review.

Piezoelectric materials exhibit an intrinsic electric polarisation. In ionically bonded materials, such as piezoelectric ceramics, the polarisation is a consequence of its crystal structure, while in crystalline polymers with aligned molecular chains it can be due to the alignment of polarised covalent bonds. Due to the polarisation, a mechanical deformation will generate an electrical charge by the *inverse piezoelectric effect* so that converting mechanical vibrations into deformation of the piezoelectric will generate an alternating electrical current. The energy density of a piezoelectric converter is strongly dependent on the coupling coefficient and the mechanical strength of the material. Roundy at al. have estimated the practical maximum energy density of piezoelectric converter to be approx. 17.5 mJ/cm³ based on a lead zirconate titanate PZT-5H material with a factor of safety of 2. [11]

The electromagnetic approach uses the relative motion between an electrical coil and a permanent magnet. The change in magnet position due to mechanical vibrations generates an electric current within the coil. The energy density is strongly dependent on the magnetic field strength and Roundy at al. have estimated the practical maximum energy density of an electromagnetic converter to be approx. 4 mJ/cm³ assuming a magnetic field of 0.1 T and a magnetic permeability of free space. [11]

Electrostatic conversion relies on the displacement of two electrical conductors separated by a dielectric material that acts as a capacitor. The voltage across the capacitor is dependent on stored charge, electrode separation, electrode area and the permittivity of the dielectric. Two modes of harvesting are possible. Firstly, if the voltage is held constant, the charge increases with decreasing electrode distance during mechanical vibration. Secondly, if the charge is held constant, the voltage increases with increasing electrode distance. In both cases the energy stored on the capacitor increases and can be extracted to power a device. Roundy at al. have estimated the practical maximum energy density of an electrostatic converter to be approx. 4 mJ/cm³ assuming an electric field of 30 MV/m (30 V/μm) and a dielectric constant of free space [11]. One aspect of this approach is that, unlike piezoelectric and electromagnetic conversion, there is a need to initially supply a charge to the capacitor element. Electret-based harvesters operate in a similar manner as electrostatic devices but the material is only charged once with a high voltage during device fabrication to induce a polarisation, eliminating the need for continuous pre-charging [12].

Electroactive polymers (EAPs) operate in a similar mode to the electrostatic conversion based devices in that the mechanical energy associated with the deformation of an electrically charged EAP is used to increase the electrical energy. If the EAP is operated as a voltage up-converter the elastomer is initially mechanically strained, electrically charged and then allowed to return to its initial thickness under open circuit conditions thereby increasing the voltage between the charged surfaces [13].

Magnetostrictive materials undergo a change in their magnetisation under the application of a mechanical stress. Such materials can produce electric energy from mechanical vibrations since they are capable of generating an electric current in a coil. The most common magnetostrictive materials include metglas, Terfenol-D, FeGa, and Ni51.1Mn24Ga24 [14].

The triboelectric effect, by which certain materials become electrically charged by friction, has recently been exploited for energy harvesting. Triboelectric generators usually consist of two material layers with a spacer in the middle. The power output depends on the cyclic contact and separation between the two triboelectric materials, which is responsible for the process of charge generation and separation. Recent contributions to the field of triboelectric vibration energy harvesting include the work of Dhakar et al. [15] and Zhu *et al.* [16].

In addition to harvesting mechanical vibrations, thermal harvesting is also an appealing technology owing to the ubiquity and abundance of heat as an essential by-product in several locations in the vehicle, including engine compartment, exhaust system and brakes. Thermoelectric energy harvesting has been widely considered as a means to convert temperature gradients into electrical energy using the Seebeck effect. A less widely researched, yet promising, area is pyroelectric energy harvesting, in which temperature fluctuations are converted into electrical energy [17].

Hybrid systems, involving the use of two or more energy transduction mechanisms, have also been investigated in the literature and will be discussed in subsequent sections of the review. Table 1 lists the basic features of the different vibration energy harvesting mechanisms, as adapted from [18].

Table 1. : Comparison of energy harvesting materials (adapted from [18]).

| Energy transduction mechanism | Advantages | Disadvantages |
|---|---|---|
| Electromagnetic | – No external voltage source | – Bulky size: magnets and pick-up coils<br>– Difficult to integrate with MEMS |
| Electrostatic | – Compatible with MEMS<br>– Voltages of 2 – 10 V | – External voltage (or charge) source<br>– Mechanical constraints |
| Piezoelectric | – Compatible with MEMS<br>– No external voltage source<br>– Voltages of 2 – 10 V | – Depolarisation with stress or temperature<br>– Brittle piezoelectric ceramics<br>– Poor coupling in piezoelectric polymers |
| Magnetostrictive | – Ultra-high coupling coefficient<br>– Less brittle than piezoceramics | – Nonlinear behavior<br>– Needs pick-up coils<br>– May need bias field<br>– Difficulty to integrate with MEMS |
| Triboelectric | – No external voltage source | – Difficult to integrate with MEMS<br>– Limited lifetime |
| Pyroelectric | – Compatible with MEMS<br>– No external voltage source | – Low power levels<br>– Requires change in temperature |
| Electroactive polymers | – Large strain capability | – Needs external voltage (or charge source)<br>– High voltages |

The most obvious sources of energy in a moving vehicle's tire are (*a*) the wheel's kinetic energy associated with spinning, and (*b*) the tire's strain energy associated with its cyclic deformation during contact with the road. Energy generators operating in these two distinct regimes have profoundly different designs in order to enable them to respond most efficiently and adapt to the nature of the incoming excitation. Table 2 classifies the basic approaches to extract energy from a rolling wheel, and highlights the most prominent energy harvesting technologies used for TPMS; this provides the reader with a map of the focus of relevant work cited throughout this review.

**Table 2. Classification of energy harvesting technologies for TPMS**

| Harvesting approach | Mechanical motion | | | | | | Fluid flow | | Other |
|---|---|---|---|---|---|---|---|---|---|
| | Kinetic energy (inertial devices) | | | Strain energy (strain-driven devices) | | Relative motion | Pressure fluctuations | Fluid flow | |
| | Flexure | Rectilinear | Rotary | Tire bending | Shock loads | | | | |
| Piezoelectric | [19]* [20] [21] [22] [23]** [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39]* | [19]* [7] [23]** [39]* | | [8], [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] | [53] [54] [6] | | [55] | [56] | [57] |
| Electromagnetic | | [58] [59] [60] | [61] [62] [63] | | | [64] [65] [66] | | [67] | |
| Electrostatic | | [68] | | | | | | | |
| Electroactive polymers (EAPs) | | | | [69] [55] | | | | | |
| Triboelectric | | | | | | [70] | | | |
| Hybrids | [71] | | | | | | | | |

* In the paper by Manla *et al.* [19], an essentially rectilinear motion of a magnet causes bending deformation of a piezoelectric element. For this reason, the entry is duplicated under flexure and rectilinear types. A similar approach using a steel ball to impact a piezoelectric device was presented by Manla *et al*. [39].
** In the work of Roundy and Tola [23], a rectilinear motion of a ball causes bending deformation of a piezoelectric element. For this reason, the entry is duplicated under flexure and rectilinear types.

## 3. Harvesting the mechanical motion of a tire

Motion-driven generators that harvest the energy associated with a rotating wheel are based on those that: (i) rely on inertia forces acting on a proof mass of a vibrating elastic structure, (ii) require a direct application of force or deformation, and (iii) rely on a relative displacement between two moving surfaces in order to generate electrical energy in a contact-less fashion, usually via electromagnetic induction. Figure 3 shows the qualitative variation of circumferential strain and radial acceleration in a typical tire rolling over a hard surface. The point at which the tire is in contact with the road is termed the *contact patch*. The surface of the inner liner of the tire on each side of the contact patch will be in compression while the within the contact patch will be in tension [8] [45]. The radial acceleration of the inner liner of the tire depends on the square of the rotational speed, but abruptly falls to zero within the contact patch.

### 3.1 Inertial devices

Inertial devices are based on the fact that the acceleration of various points on a rolling wheel, whether on the wheel rim or on the tire liner, changes with time. This time-varying motion can be used as a form of base excitation for an inertial device. The placement of the energy harvester can either be on the metallic wheel-rim or on the inner liner of the tire, which involves design modifications in the tire technology. According to Löhndorf *et al*. [9], the power spectral density of the tire acceleration in a car traveling at 50 km/h shows a rich spectrum. At low frequencies (5-20Hz) there is a strong peak corresponding to the revolution period of the wheel but there are also signal contributions up to 1 kHz. While these vibration levels depend on tire design, vehicle load, road condition, internal pressure and driving speeds, an efficient vibration energy harvester should ideally be sensitive to such a wide range of frequencies.

For TPMS applications one of the most popular configuration for an inertia-driven harvester is based on a simple cantilever beam that bends when it is attached to a vibrating host structure. In this case the vibrating structure can be the wheel rim and the beam is designed to undergo lead-lag bending oscillations as it rotates in a vertical plane. The beam usually carries a proof mass at the tip that enhances the power of the inertial device by increasing the beam deflection; the tip mass can also be used to tune the resonant frequency.

Expressions for the maximum attainable power in inertial energy harvesters have been reported by Micheson *et al*. [72] by assuming a harmonic source motion, with amplitude $Y_0$, and frequency $\omega$. An upper bound on the average power has been derived by Micheson *et al*. [72] as:

$$P_{\max} = \frac{2}{\pi} Y_0 Z_l \omega^3 m \tag{1}$$

where $m$ is the proof mass and $Z_l$ is the maximum internal displacement. Inspection of Eq. (1) reveals the linear dependence on mass and travel range, and the strong dependence on frequency. This indicates the serious challenge of designing small-scale devices that can harvest sufficient power in the low-frequency range of tire rotation for passenger cars, which is usually of the order of 20 Hz for a vehicle travelling at ~120 km/h with a tire diameter of 56 cm. Harvester performance is frequently benchmarked against this value of power [73].

Inertial devices operating within the linear regime are usually designed to operate at resonance in order to achieve maximum power generation. Accordingly, energy harvesters are typically designed to possess natural frequencies that match those of the excitation. A mismatch between the excitation and natural frequencies, due to variable rotational speed, for example, would therefore lead to a dramatic decrease in the magnitude of output power. To overcome some of these difficulties, systems with adjustable natural frequencies [62] and designs having multiple oscillators [51] have been proposed to improve the performance by encouraging resonance. The use of nonlinear behavior [58] has also been exploited to harvest energy efficiently over a wider frequency range. Gu and Livermore [36] also proposed a harvester whose natural frequency can passively track the rotational speed of a spinning rotor. For a review of wideband energy harvesting from a rotating wheel the reader is referred to the work of Wang et al. [63].

### 3.2 Strain-driven devices

Strain-driven devices exploit the longitudinal (circumferential) strain that develops in a tire when it deforms as contact is made with the road surface at the contact patch. The surface of the inner liner of the tire on each side of the contact patch will be in compression while the within the contact patch will be in tension [8] [45], see Figure 3. If, for example, a piezoelectric element is attached to the inner surface of the tire, the strains will be transferred to the harvester and an electrical charge will be generated.

### 3.3 Relative motion: electromagnetic, induction and triboelectric

In general, power generation requires some form of relative motion in which mechanical work is done on an energy conversion element. A spinning tire represents an excellent source from which various forms of relative mechanical motion can be derived without detrimentally affecting the integrity and operation of a tire. In this context, electromagnetic devices consisting of a rim-mounted magnet that rotates past a stationary coil mounted on the brake caliper [64] have been proposed. Relative motion, and the possibility of inducing cyclic frictional contact between two surfaces has also attracted interest in triboelectric based devices [74].

### 3.4 Fluid flow

Dynamic tire deformations due to motion over rough or undulating surfaces can lead to pressure fluctuations and air flow inside the tire cavity, which can be exploited for energy harvesting. For many years, extracting energy from fluid power has been accomplished by inserting rotating machinery, such as turbines, within the flow stream. While the technology is effective and well established, concerns over efficiency, cost and the reliability of smaller scale devices provides motivation for novel designs containing fewer mechanical parts. A number of investigations have recently been published on the extraction of energy from fluid flow, yet no direct application to TPMS has been made. One promising solution is to convert the fluid flow into a flow-induced vibration [56], which in turn can be converted into useful power. Reference is made to the patent by Kvisteroy and Hedenstierna [75] which highlighted the prospects of these technologies.

The previous sections have classified the harvesting approaches (e.g. piezoelectric, electromagnetic, etc.) and the mechanisms by which they are employed (e.g. inertial, deflection etc.). The following sections will now describe in detail specific systems that have been reported in the literature and related patents.

## 4 Piezoelectric harvesters

The ability of piezoelectric materials to generate an electric charge under the application of a strain has attracted the most interest as an energy harvesting material for TPMS applications.

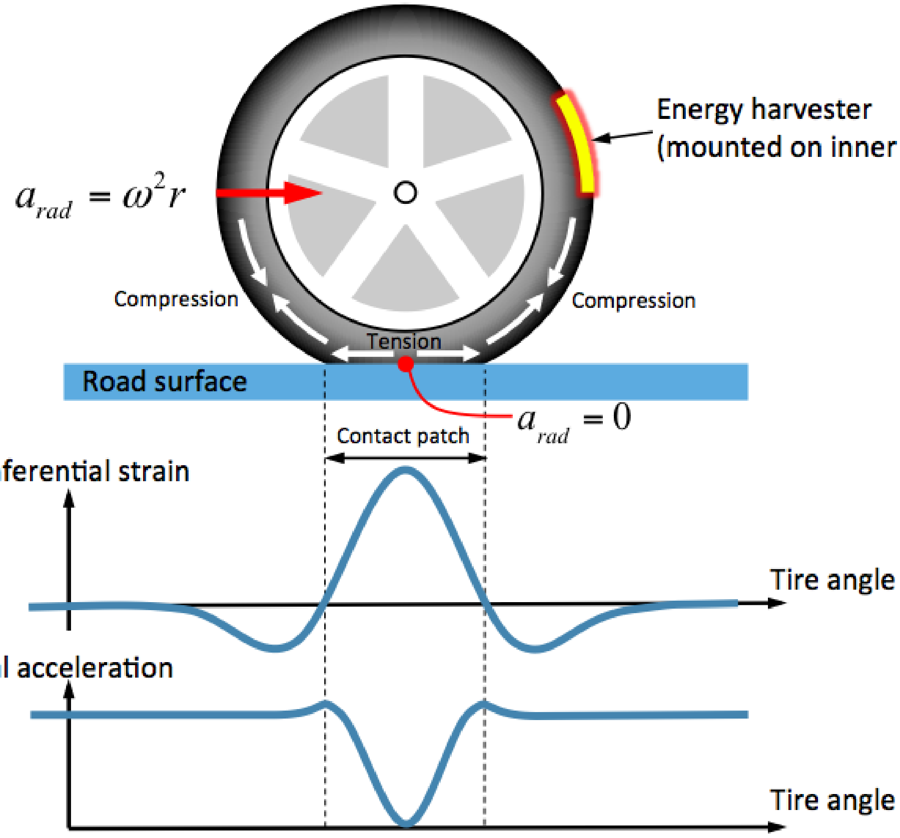



Figure 3.Variation of circumferential strain and radial acceleration in tire rolling on a hard surface. As an example the radial acceleration can be in excess of 100g at 60 km/h, the strain can reach 4000 με.

As can be seen in Table 2, piezoelectric materials and systems for tire harvesting are the most popular option and has been considered by a number of commercial companies and has also been the subject of patents; examples include Siemens [6] Piezotag [76] Eoplex [37] [77], LV Sensors [55], Pirelli Pneumatici [49] and Michelin Research et Technique SA [50].

### 4.1 Inertial piezoelectric harvesters

In an inertial piezoelectric harvester the acceleration produced as the tire makes contact with the road is used to deform a tip mass of a cantilever and the deflections are at the natural frequency of the system. For a vehicle traveling at a constant speed, the radial strain in the tire, $a_{rad}$, is constant except at the contact zone, where it abruptly falls to zero, before rising again to its steady state value. Acceleration peaks can be observed at the start and end of such acceleration changes. The tangential acceleration of the tire is zero except at the flexure points where the tire enters and leaves the contact patch. Acceleration spikes occur at these two points and can be used to apply shock loads to an energy harvester.

#### *4.1.1 Cantilever based piezoelectric harvesters*

A common approach is to harvest vibration using a piezoelectric cantilever with a tip mass at the end of the cantilever [26] [51] [38] [32] [24] [25]. Mak *et al*. [26] considered the attachment of such a configuration to the inner wall of the tire. The deformation of the tire at the contact patch leads to large radial accelerations. The potential for mechanical damage of the cantilever due to the large accelerations when the tire contacts the road is one potential concern [26], especially when relatively brittle piezoelectric ceramics are used. Bump stops were used to restrict the maximum cantilever displacement, and hence maximum stress, as can be seen in Figure 4 where the package, piezoelectric cantilever, end mass and bump stop can be observed. The piezoelectric element was a bimorph made from lead zirconate titanate (PZT) operating in 31-mode where the direction of strain is normal to the polarisation direction of the ceramic. A tip mass was used to change the natural frequency and degree of deformation. Nonlinearities due to the piezoelectric materials were also a potential issue [26], especially at high levels of stress.

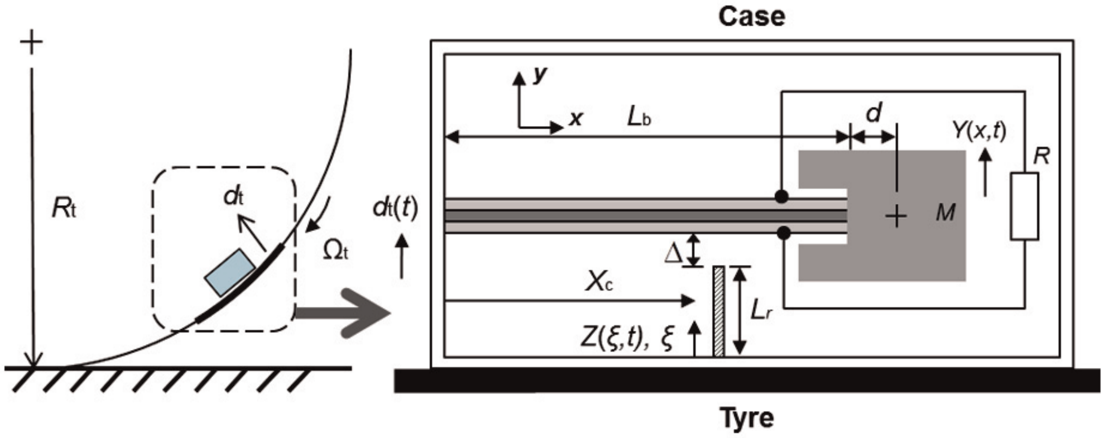



**Figure 4. Schematic of cantilever harvester showing bump stop, package, end mass and bimorph [26]. Reprinted by Permission of SAGE.**

Good agreement was observed with models of the radial acceleration experienced during wheel rotation by the harvester and literature; for example at 100 km/h the radial acceleration reaches 270g and rapidly to zero on contact with the road, in a similar way to that shown in Figure 3. One issue in terms of the harvester design is that the centripetal force produced by wheel rotation created a static offset of the cantilever from its neutral axis. For the device examined a root-mean-square power level of 178μW with a bump stop (restricted motion) and 289μW (without bump stop) under application conditions. Singh *et al*. also used bump stops to prevent failure of a piezoceramic cantilever bending element; [33] in this case the material employed was a high energy density $0.9Pb(Zr_{0.56}Ti_{0.44})O_3$- $0.1Pb[(Zn_{0.8/3}Ni_{0.2/3})Nb_{2/3}]O_3$ + $2mol\%MnO_2$ (PZTZNN) ceramic. The materials properties of relevance are listed in Table 3 along with other piezoelectric materials used in TPMS harvesting and will be discussed later.

An asymmetric air-spaced cantilever for TPMS was considered by Zheng *et al*. [34]. The advantages of such an approach was reported to be (i) the larger voltage generation due to the larger distance between the PZT piezoelectric sheet and the neutral plane, (ii) higher conversion efficiency and (iii) the ability to maintain a compressive load on the piezoceramic to reduce mechanical failure. The prototype device was road tested and the power spectrum of voltage exhibited two peaks, one at 11Hz which corresponds to the rotation rate of the tire and a second peak at 470Hz corresponding to the higher resonant frequency of the cantilever. The large difference between the tire and harvester frequency is one difficulty in achieving high powers. At 50mph (80kph) the power was 47μW and 35s was needed to charge a 32μF capacitor to 8V using a bridge rectifier. Kubba *et al*. [38] also examined an asymmetric air-space cantilever using a DuraAct transducer where the active material was a PZT ceramic.

Moon *et al*. [51] examined an array of cantilevers of different geometries (and hence natural frequencies) to allow harvesting of a range of vibration frequencies. A novel single crystal relaxor material with high piezoelectric activity was employed $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3-xPbTiO_3$. Interdigitated electrodes were employed to polarize the material along the length of the cantilever and thereby operate in 33-mode where the direction of strain is in the polarization direction. The advantage of this approach is that it uses the larger 33-piezoelectric coefficients (see Table 3 to compare 31- and 33-mode properties). A device was manufactured using a <001> PMN-PT single crystal where the interdigitated electrode was created by photolithography. A proof mass was attached the cantilever tip and at 100Hz with a 50μm deflection a power of 65μW was generated.

Eoplex have considered commercialization of a PZT based cantilever inertial harvester using a print forming manufacturing technology to manufacture the piezoelectric beam, metal conductors and mounts simultaneously [77] [37] [78]. Piezoelectric cantilevers or beams have also been the subject of patents claims for tire harvesting applications [35] [27].

#### *4.1.2 Micro-Electro-Mechanical Systems (MEMS)*

Elfrink *et al*. [53] and van Schaijk *et al*. [21] [54] of IMEC examined an AlN based piezoelectric device for TPMS and 'intelligent tire' applications where measurement of forces and driving conditions is also possible. The reported power requirement for a wireless sensor node was 1-20 μW [54]. A micro-electro-mechanical systems (MEMS) based technology was considered advantageous since it provides a route to low-cost devices that are manufactured of a wafer scale in batch mode; for example fabrication on 6-inch or 8-inch wafers [53]. It was also recognised that reducing the size of the harvester also leads to a reduced power output. A piezoelectric harvesting approach was considered over electromagnetic since it is more appropriate for micro-meter scale devices [54]; for example scaling down of pick-up coils and magnets can be complex [21]. Electrostatic based device are also applicable for micro-scale, and will be described later in the review, but if felt that piezoelectric harvesters were more mechanically reliable and potentially produce more power [21].

Based on an electromechanical model of a piezoelectric vibrator as a generic mass-spring system with a driving force the power were said to be related to the piezoelectric materials properties as:

$$P_{\max} \propto \frac{e_{31}^2}{\varepsilon_0 \varepsilon_{33}^T} \qquad (2)$$

where $e_{31}$ is the piezoelectric constant (C m$^{-2}$), $\varepsilon_{33}^{T}$ is the relative permittivity of the piezoelectric at constant stress and $\varepsilon_0$ is the permittivity of free space (F m$^{-1}$). These properties and the $\frac{e_{31}^2}{\varepsilon_0 \varepsilon_{33}^T}$ index are included in Table 3 to compare various materials used for TPMS in terms of energy per unit strain. On comparing the performance figure of merit (Eqn. 2) AlN and ZnO compares favourably to lead zirconate titanate (PZT) materials (see Table 3). Other figures of merit, such as $\frac{d_{31}^2}{\varepsilon_0 \varepsilon_{33}^T}$ and $\frac{d_{33}^2}{\varepsilon_0 \varepsilon_{33}^T}$ based of the energy per unit force in -31 and -33 direction respectively are also shown for comparison where PZT materials perform better due to higher $d_{ij}$ coefficients, a measure of charge per unit force.

The MEMS device consisted of a cantilever beam with a seismic mass (Figure 5) which was produced by deposition, lithography and etching. The active piezoelectric material, AlN, was formed on a silicon substrate. The harvesting structures where packaged in a vacuum to minimise air damping and the cantilever vibration. The reasons for selecting AlN over other materials was the ease of deposition onto silicon substrate [53], compatibility with IC fabrication methods and low loss [21].

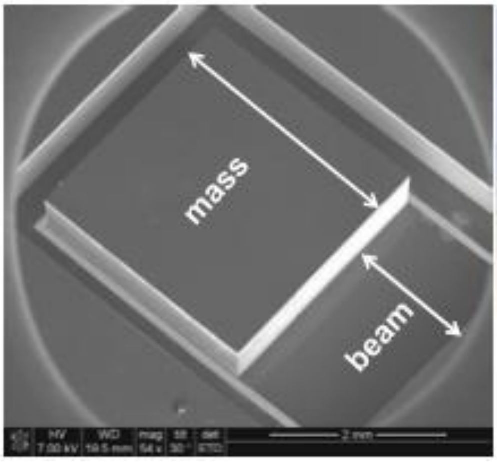



Figure 5. AlN based MEMS cantilever for TPMS harvesting. © [2011] IEEE. Reprinted, with permission, from [53].

The MEMS device was tested under a range of conditions. Under sinusoidal excitation the device resonated at its natural frequency; for example at an acceleration of 4.5g a power of 489μW was measured at 1012Hz for a device 1.7 × 3.0 × 3.0 $mm^3$ [54]. It was highlighted that one disadvantage of using the natural frequency of resonant systems, especially with high Q (quality factor) and low damping [53], is the low bandwidth which was 2.7Hz (0.27%). In addition, the high resonant frequency of the small scale MEMS device is much larger than the revolution period of the wheel. When subjected to a random noise vibration the harvester responds at its natural frequency [21]. This was said to be similar to mounting the harvester on the tire rim. Since the input noise varies with time, so does the voltage output, nevertheless power levels in the order of 10μW could be generated; sufficient for powering a TPMS module. [21]. Shock excitation as the tire contacts the road surface was also examined**.** This would be achieved if the device was mounted in the inner liner [21] and such an approach was explored to overcome the disadvantages of the high natural frequency and quality factor of the MEMS structure. For tire applications the radial acceleration is proportional to the square of the car velocity and as previously discussed can be up to hundreds of g at high speeds. At the contact patch area the radial acceleration approaches zero for a duration that is inversely proportional to the car velocity [53], as in Figure 3. Under these conditions the displacement of the tip mass, and hence piezoelectric voltage, depends on factors such as the mass and shock profile. At 60 km/h the radial acceleration was said to fall from 120-160g to small values for a period of milliseconds. Under these conditions >10 microwatts are produced, which is sufficient for intermittent TPMS (see Figure 2) but insufficient for the high sample rates needed for acceleration measurement. Since the MEMS devices exhibit a high Q the mass can still be oscillating for the preceding shock in a tire application [53] and power of 42μW was demonstrated at a speed of 70 km/h [53]. After the initial shock the device was seen to 'ring-down' at the resonant frequency with a logarithmic decay, where the duration increases with increasing Q.

Since peak acceleration can be 100g to 2900g [21] mechanical failure of the MEMS cantilever structure during shock impact is a concern but it is possible to create of package that limits beam deflection [21], as used for the larger cantilever systems. This can be designed to ensure that the maximum bending stress does not exceed that of the silicon substrate or piezoelectric. Recently Wang *et al*. reported improved reliability of such MEMS structures subject to high shock (1700g) using stoppers to limit cantilever displacement and using wet etching to reduce defect size and therefore mechanical strength. [20]

Frey *et al*. and Siemens AG also examined a piezoelectric MEMS vibration harvester [79] [80] [31] [6] [81] for a self-powered sensor node to supply 10μW at 3V. Energy management was achieved with an application specific integrated circuit (ASIC) which rectified the voltage and transferred the energy to storage [31]. When the energy storage is empty, voltage rectification was achieved by passive diodes but lower loss active rectification is employed when the energy level is sufficiently large [31]; the MEMS approach is advantageous since it allows easier integration with the rectification and storage system. The harvesting device was based on a piezoelectric thin film on a silicon carrier layer and since the device operates in 31-mode the efficiency depends on parameters such as the $d_{31}$ piezoelectric constant, $s_{11}$ compliance and permittivity. The structure was a cantilever where the piezoelectric was a self-polarised PZT thin film deposited by sputtering and the cantilever was fabricated with a triangular shape to achieve a uniform stress distribution and maximum harvested energy per unit active area, Figure 6. Again, non-resonant excitation was chosen where deformation of the tire leads to oscillation of the MEMS cantilever with a gradual decay of the amplitude and generated voltage. This approach was selected due to the high resonant frequencies of the MEMS device compared to the tire vibration levels. Based on examination of the design space of the device, such as silicon carrier layer thickness and piezoelectric thickness harvested powers of the order of 3μW could be achieved for an active area of 25mm$^2$. [6]. Air-damping was a critical factor in determining performance [80], which is typical of small scale MEMS systems.

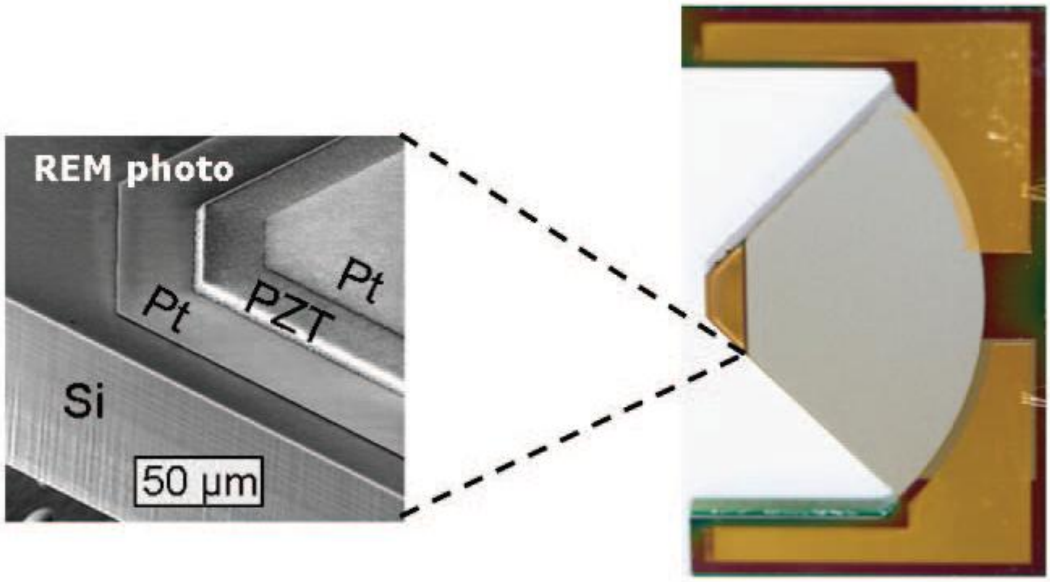



**Figure 6. Piezoelectric PZT MEMS-based harvester. © [2012] IEEE. Reprinted, with permission, from [31].**

MicroGen Systems [7] have developed Vibrational Energy Harvesting Micro Power Generators (MPGs) using MEMS technology and are also considering for tire systems.

### *4.2 Piezoelectric benders*

In terms of strain-driven types [45] the electrical charge is produced by the strain in the piezoelectric material and the device operates off-resonance and is typically attached to the inner liner of the tire. As noted by Matsuzaki and Todoroki [82], the inner surface of the tire is compressed just before the tire makes contact with the road surface; it becomes strained during contact, and then it is compressed again after contact, as in Figure 3.

Piezolectric bender devices have also been considered by Makki et al. [44] [30] [46] [41] [52]; unlike the inertial piezoelectric cantilevers these devices are often used in strain-driven mode. Two approaches were considered [44] where a PZT bender was directly bonded to the inner surface of the tire. The second approach used smaller and stiffer elements that produce charge due to a compressive load at the tire rim. Both ceramic PZT and polymeric polyvinylidene fluoride (PVDF) were considered.

*Inner wheel attachment:* When the piezoelectric bender was attached to the inner wheel, deformation of the tire at the contact patch leads to a cyclic deformation and subsequent relaxation as it leaves the contact patch [44]. PZT benders were selected since they were capable of withstanding the large deflection of the tire. A low-cost PZT unimorph device was selected where a thin PZT element was attached to a brass substrate (total thickness 0.3mm and diameter ~40mm). The advantages of PZT, compared to PVDF, were the higher electromechanical coupling factor and piezoelectric coefficient ($d_{31}$) along with a higher operating temperature since at high speeds during highway driving tire temperatures of up to 70°C can be achieved (Table 3). A flexible rubber adhesive was used for bonding the element to the tire. The power generated was stored into a capacitor and relatively large power levels (6.5mW) where achieved at a matched load resistance of 42kΩ. While this optimum load resistance is high the equivalent load impedance of a storage circuit or TPMS module can be much lower, leading to reduced power [83]. Tire mounted bender devices enabled pressure readings to be transmitted every 2.3s at 60 km $hr^{-1}$ and every 1.3s at 100 km $hr^{-1}$. PVDF bender elements were also considered but with reduced power levels, e.g. 0.8mW at a load resistance of 380 kΩ [46], although one potential advantage of such materials is their high flexibility and limited impact on tire deformation due to the high compliance of the polymer. Their poor resistance to high temperature and reduced piezoelectric activity are its main limitations, Table 3.

Scale up of the use of use of PZT bender harvested was examined by using a large 4 x 40 array of benders on the inner surface of the tire [52]. The voltage was rectified and stored in a capacitor. A large power of 2.3W was produced at a speed equivalent to 100 km $hr^{-1}$ which was doubled to 4.6W using two layers of devices. Arrays of tire mounted piezoelectric have also been subject of a patent [28].

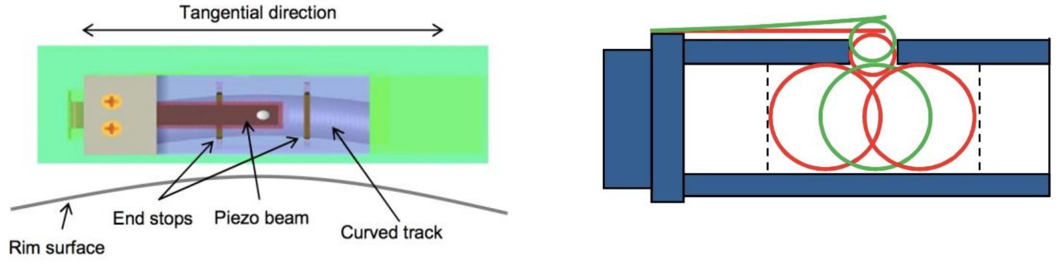
Keck [30] examined a metal-PZT bimorph structure as an inertial harvester. The device considered consisted of a beam with loose supports at both ends with a seismic mass fixed at the centre. The advantages proposed for such a system is the absence of a need for stiff clamping, unlike a cantilever, and compact integration into a package. The metal-PZT structure ensured that the piezoceramic experienced only compressive stresses to enable high deflections of the bending element, especially when combined with asymmetric motion stops. A prototype design consisted of four layers bonded together with adhesive which consisted of a high density tungsten seismic mass, a steel substrate, a PZT piezoelectric element and a thin upper electrode. Power levels of up to 40μW could be achieved 80 km $hr^{-1}$.

*Rim-wheel attachment:* Another approach was to place thin brass bender PZT elements at the tire bead and rim interface. In this case air pressure pushes the tire against the rim leading to the generation of a constant compressive force. At the contact patch the sidewalls deform so that the piezoelectric experiences an additional dynamic force. A time of 180s (240 rotations) was taken to reach a voltage threshold of 10V compared to only 6.8s (9 rotations) for the inner wheel attachment indicating the lower power generation level of such an approach [41], which was 70μW with 67kΩ electrical load. PVDF ribbons have also been considered by Makki *et al*. [46] whereby the piezoelectric element is not directly bonded to the tire, but is bonded to the bead section and the ribbon is deformed as the tire height or width changes during rotation, such an approach produced a power of ~0.2mW.

### 4.3 Rotational devices.

A different approach to inertial or direct-strain is to develop rotating harvesting approaches. Gu and Livermore presented passive self-tuning harvesters [29] [36] using rotation. One type of device consists of two beams that rotate in the vertical plane, the first beam is a rigid piezoelectric generator that is mounted adjacent to a second more flexible driving beam with a tip mass mounted at the end [29]. The tip mass of the driving beam impacts the piezoelectric beam to generate power and the centrifugal force of rotation is used to change the resonant frequency of the harvesting system. Both PZT and PVDF piezoelectric beams were examined where the PZT beam produced a power of 123μW at 15Hz (~100 km $h^{-1}$) corresponding to a power density of 30.8 μW $cm^{-3}$ and the self-tuning enabled a bandwidth of 11Hz. The output of the PVDF beam was lower at 27μW at 15Hz with a 9.5Hz bandwidth, although the mechanical reliability was improved due to the higher toughness of the polymer.

Roundy *et al*. [23] examined harvesting devices that rotate through the Earth's gravitational field and the axis of rotation is parallel to the Earth's surface, such as in TPMS applications. By exploiting the dynamics of an offset pendulum mounted on a rotating wheel, a broadband frequency response was achieved. A prototype device consisted of a curved track with a radius smaller than the rim radius for offset pendulum dynamics (Figure 7a). The proof mass was a steel ball that rolled back and forth along the track. Two piezoelectric beams were applied along the track and both the piezo-beam and steel ball make contact as the ball, rolls past, leading to power generation (Figure 7b). A piezoelectric beam was used over an electromagnetic approach due to the higher voltages of the piezoelectric, especially at low frequencies. The interaction of the proof mass with the piezoelectric beam and spring loaded end stops was shown to alter the spring constant of the system and, when combined with a gravitational force, the system behaved as a bi-stable oscillator. At high rotational speeds the system behaved as a linear system since the centripetal acceleration dominates the restoring force that stems from the interaction of the proof mass with the piezoelectric beam. The system was reported to have a higher bandwidth compared to a simple linear oscillator and simulation predicted power of approximately 100µW at 60mph.




(a) (b)

**Figure 7. (a) Rotation harvester device concept; (b) piezoelectric beam is undeflected when the proof mass ball is in left or right position (shown in red) and piezoeletric beam is deflected when proof mass passes centre position (shown in green). © [2013] IEEE. Reprinted, with permission, from [23].**

Manla *et al*. [7] [39] considered a kinetic harvster that consisted of a tube with a piezoelectric transducer at each end which allows a ball bearing to move freely and impact on the transducers. The system would be mounted on the vehicle rim. A $2cm^3$

generator produced 4mW at 800rpm. In addition to cantilever and bender configurations other rotational approaches have been considered; for example Khameneifar *et al*. [22] considered an array of piezoelectric stacks connected by small springs to make a flexible ring which deforms at the contact patch. An analytical model predicted ~3mW at an optimum load resistance. Harvesting from airless tires has also been considered [57].

### 4.4 Direct deformation of piezo-nanogenerators and piezo-composites

In addition to bulk materials and films deposited on silicon substrates, nanoscale materials and composites have been explored. Hu *et al*. examined piezoelectric nanogenerators [48] which when strained generate a transient flow of electrons across an external electrical load. The nanogenerator was attached to the inner surface of a bicycle, as in Figure 8, which shows the tire deformation in relation to the contact patch. Based on the working area of the device a maximum power output density of 70 $\mu$W cm$^{-3}$ was achieved and the energy was used to light a liquid-crystal display. The nanogenerator was designed as a free-cantilever beam structure consisting of five layers with a central flexible polyester substrate with piezoelectric ZnO nanowire textured films on the upper and lower surfaces of the substrate and conductive electrodes on upper and lower surfaces. Correlations between the amount of tire deformation with nanogenerator output voltage also allowed the system to act as a sensor; for example a higher voltage was developed as the speed of tire rotation increased.

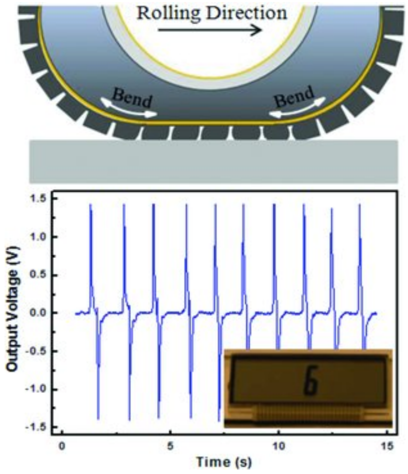



**Figure 8. Schematic of nanogenerator deflection when attached to the inner surface of a tire along with voltage output and LCD screen that was lit by the nanogenerator [48]. Reprinted by Permission of Wiley.**

Ferroelectric ceramics such as PZT are brittle and can change stiffness and polarisation at high strains due to ferroelectric domain motion. [45]. As Table 3 shows, the PVDF piezoelectric poylmer is compliant, and tough, but has insufficient thermal resilience for tire harvesting [45] since temperatures can be up to 80°C. Composite materials have therefore been considered for TPMS harvesting to combine the advantage of high piezoelectric activity of ferroelectric ceramics, such as PZT, with the flexibility and compliance of a polymer material. These materials were considered by direct bonding to the inner tire [45]. Lee *et al.* considered a composite device [47] based on PZT fibres in a polymer matrix. Interdigitated electrodes were used along the material length to ensure the poling direction was in the main axis of deformation and hence the device is operating in a 33-mode [40] rather than a 13-mode. The strain differences between the tire, adhesive layer and energy harvesting materials were also considered my modelling. By attaching a piezoelectric composite patch 60mm x 10mm and bonding to the tire with an epoxy substrate of 0.5mm thickness a power of 1.37μW/mm$^3$ was achieved.

Van de Ende *et al*. provided a detailed examination of a range of PZT-polymer composites [45] containing PZT granules or fibres along with a comparison with conventional/commercially available materials. Composites examined consisted of PZT powder randomly mixed in a polymer matrix and PZT that was structured (textured) using dielectrophoretic (DEP) processing. Composites with short PZT fibres structured by DEP were also considered. The materials were bonded to the inner surface of tires using a cyanoacrylate adhesive. While the power output of the composites where lower than commercial macro fibre composites (MFC) and PVDF films they demonstrated improvements in other properties. For example, the composites exhibited higher strain capability than the MFC and were better than PVDF at the high temperatures associated with tires. As an example, the short fibre DEP composites provided a power of 30μW/mm$^3$ at relatively low speeds of 50 km hr$^{-1}$. Piezoelectric fibres as a source of harvesting have been considered in a patents by Adamson *et al*. [42] [43].

### 4.5 Fluid flow

Wang *et al*. [56] developed a vortex induced vibratory device featuring a piezoelectric diaphragm, and later demonstrated a similar technique using an electromagnetic energy harvester [67]. Roundy *et al*. patented a device whereby pressure changes in a tire are used to generate electricity from a piezoelectric device [55]. The average power that could be generated was approximately 120 mW/mm$^2$ of transducer area.

## 5 Electromagnetic harvesters

Electromagnetic induction, which relies on the relative velocity of a magnet and a coil, has long been used for energy generation. Renewed interest in this technology has been spurred by the widespread use of TPMS as a viable application platform, especially when low-cost solutions are needed for mass-produced automotive parts. The generation of some relative motion between two surfaces in a spinning tire can be accomplished in numerous ways. One approach is to use inertial devices, wherein a levitated magnet is driven past stationary coils in a device that is mounted on the wheel rim [64]. Inertial harvesters that are embedded in the inner liner of the tire have also been proposed [58]. Efforts to use electromagnetic coupling for energy harvesting have been reported by Visityre [6]. Electromagnetic harvesters for TPMS usually consist of magnets that move linearly or rotationally, unlike many piezoelectric generators that often take the form of cantilevers.

### 5.1 Inertial electromagnetic harvesters

A novel inertial harvesting device has been reported [58] which is mounted on the inner liner of a tire. The frequency spectrum and amplitudes of the resulting vibrations vary with time according to the vehicle speed and road terrain, see Figure 9a and share similarities with the schematic in Figure 3. The harvester uses magnetic levitation to drive a permanent magnet across a coil as a result of tire contact with the road, as illustrated in Figure 9b. Thus, an efficient vibration generator must be custom designed for the target application [5].

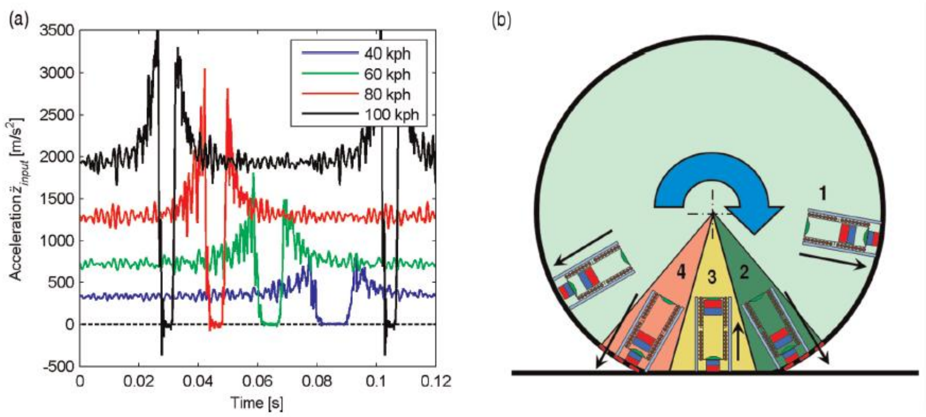



**Figure 9. (a) Typical radial acceleration profile at different speeds for a point on the tire inner liner, similar to that in Figure 3; (b) proposed energy harvester where magnet is deformed relative to a coil [58]. Reprinted by Permission of SAGE.**

Another electromagnetic device to capture energy from a spinning wheel was proposed by Chen *et al*. [59]. The device was composed of a proof mass made of permanent magnets, two springs, a coil and an energy storage circuit. The rotating wheel produces a centrifugal force while the proof mass is subjected to a pull force by one spring and a push force by another. The proof mass vibrates along the transverse direction due to the variations of the gravity. For a specific spring constant ratio of the two springs, the natural frequency of the spring-mass system can be adjusted by the centrifugal force of the rotating wheel and allows the proof mass to vibrate with large velocity and displacement. A numerical study revealed that the amplitude of the displacement was more than 1 mm and the converted electrical power was more than 100 μW. Efforts to design rim-mounted harvesters also include the work of Lee *et al*. [61], in which an arm carrying a tip mass was designed to rotate while the tire spins. It was reported that the device successfully charged a battery with 16 mJ after 200 cycles of rotation.

Hatipoglu and Urey [60] exploited the change in acceleration at the tire-road contact to create a harvester with a resonance frequency of 46 Hz constructed from an FR4 spring. Under acceleration profiles that mimic the tangential accelerations encountered by a rolling wheel, a power output of 0.4 mW was achieved. However, as with many intertial based harvesters they are often designed as resonant devices whose natural frequencies should ideally match those of the excitation. However, the input excitation for tire applications is both frequency-varying and relatively low; typically 10-20 Hz. This resonant behavior of such harvesting devices is particularly disadvantageous in systems with high quality factors (Q) since a deviation from resonance leads to a substantial reduction in the output power. As a result there has been interest in the design of harvesting devices that respond to a wide bandwidth to maintain an acceptable level of harvested power. Several approaches have been adopted which include systems with frequency-adjusting capabilities using weighted pendulums [62] have been proposed to respond to a wide range of vehicle speeds. The use of nonlinear behavior [58] has been exploited to harvest energy efficiently over a broad frequency range. For a review of wideband electromagnetic energy harvesters that are specifically designed for rotating wheels, the reader is referred to the work of Wang *et al*. [63].

### 5.2 Relative displacement: electromagentic & induction

Wang *et al*. [66] reported an energy harvesting system on a rotating wheel where the rotational motion of the tire was used to harvest power. The design was based on a magneto-static coupling between a stationary circular-arc hard magnets array and rotating magnetic coils with high permeability magnetic materials, which leads to significantly enhanced output power density. One advantage of this approach is that a conventional tire pressure sensor can be readily adapted for this purpose. An average power density varying from 1 to 5 W/cm$^3$ at a variety of tire rotation speed was demonstrated. A numerical and experimental study to power a real-time wireless TPMS has been conducted.

Designs featuring tire-mounted, as well as rim-mounted harvesters have been reported in the literature for this purpose. Lee and Kim [64] attached a thin coil strap with a magnetic sheet layer on the circumference of a rim and placed a permanent magnet on the brake caliper system. As the tire rotates, the relative motion between the magnet and the coil generates electrical energy by electromagnetic induction. Experiments conducted on a bicycle wheel rotating 200 rpm (wheel speed of 24.9 km/h) yielded a mean power of 3.05 mW, which is commensurate with the power required for RF data transmission in a modern TPMS being 200-250 μW. A similar design has been proposed by Park *et al*. [65].

## 6 Electrostatic harvesters

IMEC and Panasonic have developed a vibration energy harvester based on electrets; these are dielectric materials that have a quasi-permanent electric charge or dipole polarisation [5]. The MEMS based device had a footprint of only 1cm$^2$ and was developed for tire pressure monitoring systems (TPMS). The maximum power generated was 160μW when excited by a sinusoidal vibration. Under noise vibration, as would be experienced in tire applications, the generated power was between 10 and 50μW, which is enough to power a simple TPMS module. Details of how the rectilinear input vibration will be generated from the spinning tire have not been disclosed. Löhndorf et al. [9] showed that MEMS-based electrostatic vibration energy harvesters can deliver an average power of up to 10μW to supply a TPMS.

Westby and Halvorsen [68] designed a one-dimensional micro-scale electret-based energy harvester for TPMS systems, located on the inner liner of the car tire. The device made use of the centripetal accelerations present in a car tire. With a device containing a silicon proof mass measuring 400 μm × 3.8 mm × 4.34 mm mounted on the tire of a vehicle traveling at 50 km/h, an output power of 4.5 μW was generated, which is sufficient for TPMS applications (see Figure 2).

## 7 Hybrid systems

The investigation of hybrid systems, i.e. those involving two or more energy transduction mechanisms, have attracted attention for TPMS. These systems are designed to enhance power output and to utilize the materials in their best operating conditions. Hybrid approaches combined piezoelectric and magnetic systems have been examined.

Manla *et al*. [19] used a non-contact piezoelectric harvester that is deformed by an interaction of a piezoelectric with oscillating magnets. The system was directed towards TPMS applications and mounted on a rotating object to extract electrical power. Pre-stressed PZT piezoelectric beam elements (a 'Thunder') were used for enhanced mechanical stability; the 'Thunder' device consisted of three-layers where the bottom layer is a stainless steel, the top layer is aluminium and the middle layer is a PZT ceramic. The thermal mismatch between the three layers during manufacture results in a pre-stress in the transducer thereby allowing large deflections without mechanical failure. The hybrid harvesting device consisted of a tube with a Thunder piezoelectric beam mounted at each end, and is shown in Figure 10.

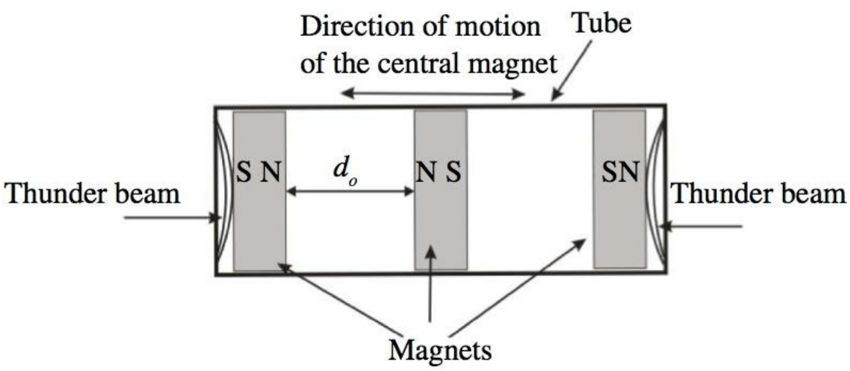
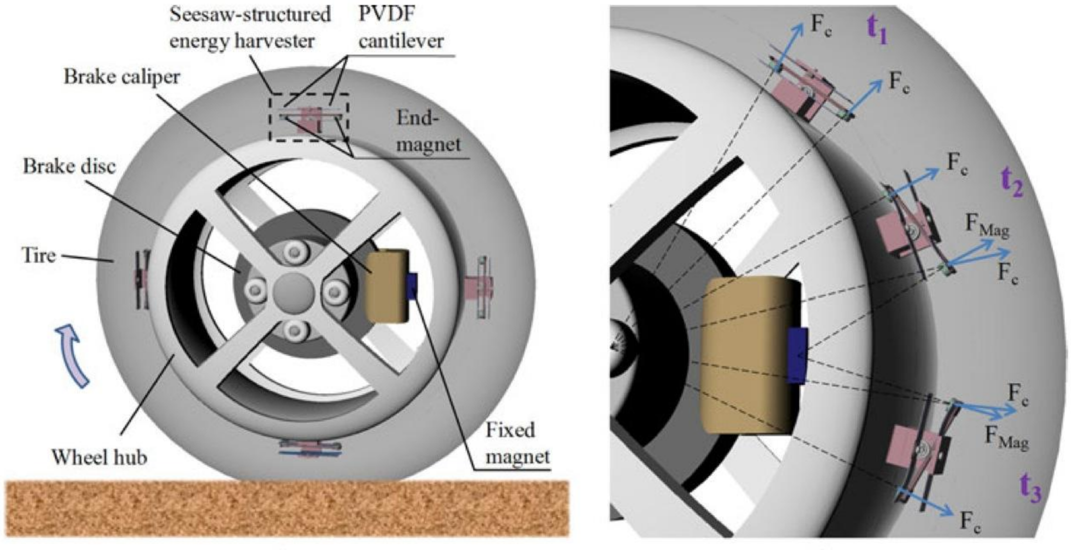



**Figure 10. Hybrid energy harvester proposed by Manla et al. © [2012] IEEE. Reprinted, with permission, from [19].**

A central magnet was placed axially in the tube and was in line with two outer magnets and the poles of the outer magnets were orientated to repel the central magnet. When rotational forces are developed during tire rotation the central magnet moves between the outer magnets and the outer magnets generate a force on the piezoelectric transducers at the ends of the tube. In this configuration there is no direct contact between the moving central magnet and the piezoelectric. Power levels up to 3.5μW were generated a 5.55 Hz.

Wu *et al*. [84] considered a novel seesaw-structured energy harvester for TPMS. Device performance was said to be independent of rotating speed to provide a broadband response. Two magnets were placed on a seesaw structures (Figure 11) which are excited by magnetic repulsive forces that were generated by a permanent magnet mounted on the brake caliper. The excitation of the seesaw structure during each rotation leads to it impacting al a PVDF cantilever to create power. A peak power of 36μW was achieved at an optimum load of 0.6MΩ with a broadband response. At 750 rpm an average power of 5.6μW was achieved, sufficient for TPMS.




(a) (b)

**Figure 11. (a) Seesaw-structured energy harvester, (b) close up view proposed by Wu et al., © [2012] IEEE. Reprinted, with permission, from [84].**

Matching the tire's angular velocity to the natural frequency of the embedded (wheel-mounted) harvester is a desirable aspect to achieve maximum power output. The use of manually tunable devices is obviously not a feasible solution and devices that automatically adjust their own natural frequencies are unlikely to be viable since feedback control requires external power as well as additional space and complexity for actuators. To overcome these obstacles, the use of passive, self-adjusting harvesters is of interest. A promising solution [36] relies on the concept that an axial tensile force applied on a rotating cantilever beam can change its natural frequency due to centrifugal effects. In this way, the tensile stresses due to centrifugal forces in a rotating beam were exploited to tune its natural frequency so that the beam remains at or near its resonant frequency over a range of rotational speeds. Since the centrifugal force is proportional to the square of driving frequency, the resonant frequency of an optimized harvester can track and match the driving frequency over a wide frequency range. The idea is illustrated in Figure 12, which shows a radially oriented beam [71] that is mounted on a base that rotates in a vertical plane. In this manner, gravity bends the beam in one direction as it rises and in the opposite direction as it falls. This repeated bending of the hybrid magnetostrictive/piezoelectric beam produces electricity. At a rotational speed of 588 rpm, a power of 157 μW was obtained across a 3.3MΩ resistor. The concept has also been presented by Gu and Livermore [29] where the cantilever beam's natural frequency was designed to track the rotational speed under the effect of the centrifugal stiffening forces.

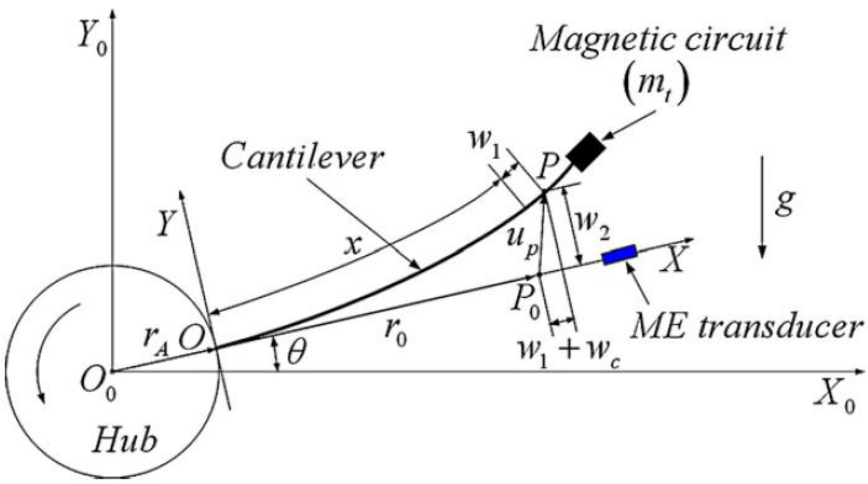



Figure 12. Schematic illustration of frequency-tunable energy harvester [71] with permission from Elsevier.

## 8 Other approaches for TPMS energy harvesting

### 8.1 Tribo-electric nanogenerators

Zhang et al. [70] examined low-cost and robust single electrode based rotating tribo-electric nanogenerator (SR-TENG) to convert rotation from tires into electric energy; the single electrode configuration was seen to particularly suited to making electrical connection with rotating tires. The device consisted of a rotating acrylic disc with adhered polytetrafluoroethylene (PTFE) blades and an aluminium foil where the PTFE is the triboelectric material and the aluminum served as both a triboelectric and electrode material. Eight PTFE units were deployed on a wheel with a single static aluminium electrode which was used to power 30 LEDs. Power values of up to 30μW were produced at a rotation of 800 r/min with an output voltage of 55V.

### 8.2 Electro-active polymers

Surprisingly limited studies have examined the potential application of electro-active polymers (EAPs) for harvesting from a tire. Martineau [69] patented an approach to use EAP generators to recover the mechanical deformation of a tire and the EAPs were considered well suited for the application since they can tolerate the high strains (>200%) associated with tire deformation. A variety of internal structures were proposed with radial and lateral arrangement of the transducers to develop strain. Roundy et al. [55] also described the use of EAPs in a patent.

### 8.3 Non-contact energy delivery

The use of non-contact power transmission technologies, such as radio-frequency identification (RFID) has attracted several investigators [4] [85] to implement these systems in TPMS. The basic architecture of these systems consists of a transmitter that is mounted on the car frame outside the tire and a receiver that is placed inside the tire and the energy is transferred through inductive coupling. Power recovery circuits are required to generating stable DC voltage by filtering and stabilizing the AC signal received.

### 8.4 Surface Acoustic Wave (SAW)

Another battery-less TPMS has been developed by Stack [86] that uses Surface Acoustic Wave (SAW) sensing technology to dynamically measure tire pressure and temperature. The SAW sensor elements require no supporting electronics or battery. Each TPMS sensor is mounted internally within the tire, either on the rear of the valve stem, or directly on the wheel rim. A central module 'interrogates' each wheel sensor in turn, by transmitting an RF 'power' signal. Three SAW elements inside the TPMS sensor each re-transmit a specific RF frequency, corresponding to the pressure and temperature inside the tire. The interrogator receiver picks up the SAW RF signals and converts them into pressure and temperature data, which are transmitted for use by a data logger and/or driver display. When the system is not in use, the TPMS sensors are completely passive, not emitting any RF signal. Stack's battery-less TPMS has extended the inherent sensor life from 1-5 years to 10-15 years.

## 9 Circuits and storage

A complete energy harvesting system usually consists of an energy transducer that converts the ambient energy into electrical energy, an interface circuit that conditions and regulates the output signal, and an electric load that stores or consumes the generated energy. As the electric output of an energy harvester is usually insufficient to power the electric load directly, power electronic interface circuits are required to convert the output signal into a regulated output voltage that is compatible with the load electronics. To ensure maximum extraction of power from the harvester, as well as maximum transfer of power to the load, proper rectification, transfer, accumulation and utilization of the scavenged energy must be accomplished. The design of interface circuits in TPMS is particularly challenging, since the magnitude of generated power seldom exceeds a few milli-Watts, which imposes significant design constraints on the development self-contained systems with advanced functionalities. Power losses and intermittency are key issues for TPMS circuitry. Furthermore, hardware ruggedness is essential to enable safe operation in the harsh environments of an automotive tire. Accordingly, power electronics concepts (control, devices, and circuit topologies) reported in the energy harvesting literature are subject to design tradeoffs that are somewhat different to those for higher power applications where the overheads of power losses due to quiescent current, for example, is less significant [87].

A comprehensive review of power conditioning techniques for piezoelectric and electromagnetic transduction mechanisms has been reported by Szarka *et al*. [87]. These harvesters produce essentially Alternating Current (AC) signals, thus power conditioning circuits should provide efficient rectification (AC-DC conversion) of the incoming AC power in order to meet the needs of most electronics, while drawing minimal quiescent current. This can be attained by a rectifier bridge and a smoothing capacitor, though more sophisticated circuit topologies have been proposed to increase the efficiency and to alleviate problems associated with forward voltage drop and leakage current through active rectification. Such passive and active rectification techniques, in addition to voltage conditioning (rectification, conversion and regulation), and power regulation issues were also discussed by the authors. One difficulty with active circuits, however, is that they require their own power supply, hence the design of self-sufficient harvesters, those that produce more power than they consume, becomes a challenge. Additionally, regulation and level shifting of the output voltage may be required by the load electronics. This is often accomplished by a DC-DC converter to enable maximum power transfer to the load or storage device (battery) through impedance matching. Dicken *et al*. [88] analyzed several interface circuits for piezoelectric energy harvesters that either dissipate energy in a resistive load or store energy in a battery or capacitor. The circuits analyzed can extract more energy than a simple bridge rectifier by actively modifying the voltage on the piezoelectric capacitance. Power harvesting circuits ranging from simple passive diode rectification to efficient active converter circuits with intelligent control, synchronized switching and power conditioning have been reviewed by Priya & Inman [89]. Other useful reviews of energy harvesting circuits can be found in [90] [91] [92] [93] [94].

## 10 Concluding remarks and future prospects

The desire to develop self-powered automotive sensors has resulting in extensive research in recent years on energy harvesting. The potential for embedded autonomous sensors open up the avenue for incorporating more systems and sensors for increased functionality without detrimentally affecting the vehicle design and weight. This review has covered the current state-of-the-art in energy harvesting systems that are specifically designed for TPMS. Efforts to augment energy harvesting functionality to tire pressure sensors are worthwhile since the installation site of these sensors in rotating wheels prohibit the use of any form of hard wires for data transmission or power. A central challenge addressed is securing sufficient and sustainable power for TPMS for autonomous operation by making use of the tire rotation as an essentially inexhaustible source of energy. The challenge is to (a) harvest sufficient amounts of energy from the tire as the vehicle moves and different speeds over undulating roads, (b) design rugged energy harvesting systems to withstand the harsh operating conditions dictated by the application, (c) integrate the system components in a single platform that can be mounted inside the tire with little or no design modifications.

By harvesting energy from the environment, significant progress can be achieved towards (a) extending the useful life of TPMSs, (b) alleviating the environmental risks associated with battery disposal, and (c) reducing the installation and maintenance costs incurred with the traditional battery-powered alternatives. To give the reader an overview of the widely-adopted methodologies, a map is presented in Table 2 showing where each reference fits, in terms of which source of energy is tapped into, and how the energy is converted. Inspection of Table 2 reveals that piezoelectric materials have been the most popular class of materials used are the. The use of other materials, such as magnetostrictive materials, remains to be investigated, especially that magnetostrictive materials offer advantages over piezoelectric materials, most notably higher energy conversion efficiency, longer life cycles, lack of depolarisation and higher flexibility. By far the most common approach examined to date his harvesting mechanical vibrations, less effort had examined the thermal energy associated with the higher temperature ties, for example use of thermoelectric or pyroelectric harvesting approaches.

Based on the present review, there are a number of open challenges:

First, although the energy harvesting community has been aggressively researching new materials and designs to harvest energy from mechanical vibrations, less attention has examined situations where the driving frequency is variable, as in the case of automotive tires. The use of self-tunable devices and broadband harvesters is particularly useful in such applications.

Second, the rotational frequencies encountered in automotive tires is low and normally do not exceed 20 Hz, which imposes significant limitation on the magnitude of power harvested. This imposes design constraints on rim-mounted inertial devices, which are usually designed in the form of base-excited resonators. One way to alleviate this obstacle is to mount the energy generators onto the tire, thereby exploiting the larger levels of accelerations and shock loads associated with tire deformation and road contact. This solution, however, causes inevitable design modifications in the tire since the energy generators as well as matching electronic circuits must be embedded in the tire itself. In this context, the design of novel nonlinear resonators, especially those that exhibit of bi-directional stability, becomes particularly attractive for broadband vibration energy harvesting.

Third, space limitation adds a considerable constraint in designing compact energy harvesters that do not add much unbalance to the tire yet generate enough power for the TPMS. Progress in MEMS devices, piezoelectric materials and composites has resulted in more energy-efficient conversion materials, which is opening up new avenues for research in materials science. On the other hand, the design of frequency up-conversion mechanisms to maximize the amount of energy harvested in a given space is appealing. Using this approach, a slowly-varying input motion can be converted into high frequency oscillation for enhanced power generation. Such a design is ideally suited for harvesting low-frequency wideband vibration, typical of tire motion. This enables the integration of all the system components on a self-contained embedded platform to wirelessly transmit pressure data.

Finally, the energy harvesting device often produces little average output power and the power is often discontinuous and unregulated and does not lend itself to being used directly for powering electronic circuits. This challenge can be addressed by the design a power manager circuit that provides load matching to the vibration harvesting device impedance for optimal power transfer, and that requires little current to manage the accumulated energy and produce regulated output voltages with as few discrete components as possible. In addition the complete system must be at a sufficiently low-cost to be deployed in every tire.

While there remain significant challenges, the increased legislation for greater use of TPMS systems, the large energy associated with tire rotation, the reduction in power requirements for wireless sensor systems and improvements in energy harvesting materials and devices means that interest in energy harvesting approaches for powering TPMS is likely to continue to gather interest both academically and commercially.

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**Table 3. Piezoelectric, dielectric and mechanical properties of piezoelectrics used for TPMS harvesting**

| Material | AlN | ZnO | PZT-4 'hard PZT' | PZT-5H 'soft PZT' | PZTZNN | PMN-33PT | PVDF |
|---|---|---|---|---|---|---|---|
| Const. strain rel. perm. ($\varepsilon^{s}_{33}$) | 10.0 [95] | 8.84 [96] | 635 [97] | 1470 [97] | 475 [33] | 680 [98] | 5-13 [99] |
| Const. stress rel. perm. ($\varepsilon^{T}_{33}$) | 11.9 [100] | 11.0 [96] | 1300 [97] | 3400 [97] | - | 8200 [98] | 7.6 [101] |
| $d_{33}$ (pC $N^{-1}$) | 5 [102] | 12.4 [103] | 289 [97] | 593 [97] | 167 [33] | 2820 [98] | -33 [101] |
| $d_{13}$ (pC $N^{-1}$) | -2 [102] | -5.0 [103] | -123 [97] | -274 [97] | -53 [33] | -1330 [98] | 21 [101] |
| $e_{33}$ (C $m^{-2}$) | 1.55 [104] | 1.32 [104] | 14.1 [105] | 23.5 [106] | - | 20.3 [98] | -0.276 [105] |
| $e_{31}$ (C $m^{-2}$) | -0.58 [104] | -0.57 [104] | -4.1 [105] | -5.26 [106] | - | -3.9 [98] | -0.130 [105] |
| Mechanical quality factor ($Q_m$) | 2490 [107] | 1770 [107] | 500 [97] | 65 [97] | 673 [33] | 43-2050 [108] [107] | 3-10 [109] |
| Electro-mechanical coupling ($k_{33}$) | 0.23 [107] | 0.48 [103] | 0.7 [110] | 0.75 [110] | 0.45 ($k_p$) [33] | 0.94 [98] | 0.19 [111] |
| $s^{E}_{11}$ ($pPa^{-1}$) | 2.854 [112] | 7.86 [113] | 12.3 [97] | 16.4 [97] | 10.5 [33] | 69.0 [98] | 365 [101] |
| $s^{E}_{33}$ ($pPa^{-1}$) | 2.824 [112] | 6.94 [113] | 15.5 [97] | 20.8 [97] | - | 119.6 [98] | 472 [101] |
| Density (kg $m^{-3}$) | 3230 [104] | 5610 [104] | 7500 [104] | 7500 [104] | 7500 [33] | 8060 | 1780 |
| Operation temperature or Curie temperature (°C) | >500 | - | 328 | 190 | - | 160 | 80 |
| Merit index (C $m^{-2}$)$^2$; $\frac{e_{31}^2}{\varepsilon_{33}^T}$ | 0.028 | 0.029 | 0.013 | 0.008 | - | 0.002 | 0.002 |
| Merit index (pC $N^{-1}$)$^2$; $\frac{d_{31}^2}{\varepsilon_{33}^T}$ | 0.34 | 2.27 | 11.64 | 22.08 | - | 215.71 | 58.07 |
| Merit index (pC $N^{-1}$)$^2$; $\frac{d_{33}^2}{\varepsilon_{33}^T}$ | 2.10 | 13.98 | 64.24 | 103.42 | - | 969.8 | 143.2 |

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